

**RAPORTY IChTJ. SERIA B nr 1/2018**

**PRE-FEASIBILITY STUDY OF SETTING UP  
AN ELECTRON BEAM R&D FACILITY**

**Zbigniew Zimek**

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## **AUTHOR**

Zbigniew Zimek

*Institute of Nuclear Chemistry and Technology, Centre for Radiation Research and Technology*

The work was performed in the framework of Horizon 2020 Programme, project H2020-INFRAIA-2016-2017 “Accelerator Research and Innovation for European Science and Society” (acronym: ARIES), grant agreement No. 730871

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## **EDITORIAL OFFICE**

Institute of Nuclear Chemistry and Technology

Dorodna 16, 03-195 Warszawa, Poland

phone: 22 811 06 56, fax: 22 811 15 32, e-mail: [sekdyrn@ichtj.waw.pl](mailto:sekdyrn@ichtj.waw.pl)

[www.ichtj.waw.pl](http://www.ichtj.waw.pl)

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## **Pre-feasibility study of setting up an electron beam R&D facility**

Electron beam is commonly accepted as an instrument for research study and industrial implementation in various fields of applications such as sterilization of medical items, crosslinking of insulation in wires and cables, modification of polymers properties and other radiation technologies. The importance of radiation technology is related to unique properties and quality improvement of irradiated products. Technical and economical parameters of radiation facility should be evaluated before initiation radiation processing practical implementation. The present report provides the assessment which was carried out. The technical and economical pre-feasibility study related to installation accelerator facility was performed. It was based on comprehensive technical and financial profiles of the technology represented by four different accelerators implementation.

Radiation processing is usually based on moving conveyor and scanned electron beam which provides possibility to irradiate cartons containing modified (or sterilized) products. It should be noticed that sometime two-sided irradiation is applied for certain product dimensions at density even for electron energy range as high as 10 MeV. Radiation facility located at the Institute of Nuclear Chemistry and Technology (INCT) has been build, towards higher technical and economical effectiveness, better operational characteristics suitable for radiation processing and research programs in order to promote in Poland the radiation processing technologies where high energy electrons are required. The objective of the home made project was 10 MeV, 10 kW linear electron accelerator equipped with microwave source based on modern klystron device and standing wave accelerating section. Similar accelerator construction is offered by CORAD Company (Saint Petersburg, Russia). It was designed for installation inside of industrial buildings or warehouses.

Resonant HF accelerators are based on the large resonant cavities working in the frequency range of one to several hundred MHz. Those cheap and reliable accelerators require relatively simply and compact HF generators. Medium and high electron energy level with appropriate beam power can be obtained. ILU type electron accelerators provided by the Institute of Nuclear Physics (INP, Novosibirsk, Russia) are based on one coaxial resonator operating in pulse regime covering energy range up to 5 MeV with average beam power up to 20 kW. Finally, Rhodotron type electron accelerator provided by IBA (Belgium) based on multipass concept of electron beam arrangement was also included to the comparison. Accelerator is characterized by continuous beam operation but with RF modulation of the electron intensity. The compact construction, relatively high (up to 50% of electrical efficiency) energy 5-10 MeV and high beam power make this accelerator suitable for wide range of industrial applications.

Radiation facility assumed to be operated 46 weeks/year due to typical accelerator availability level, holidays and maintenance periods, what corresponds 1840 h/year (8 h for 5 days/week). The total operation time with electron beam is limited to 1552 h/year (one shift) because of daily switching off and on procedures. The investment and operating costs for electron beam accelerators vary widely because of different accelerator specification, type of accelerator and accelerator producers price policy. High facility throughput which is directly related to the beam current level may significantly reduce total unit cost of the process. The accelerators with higher energy of electrons cost more than low energy devices with the same beam power level. Therefore, the lowest energy rating with suitable dose distribution in irradiated object will give better economical parameters of the radiation process. A reduction of the operating time would increase the unit cost significantly because fixed annual cost of investment will be allocated to fewer hours of accelerator exploitation. The detailed analysis should be performed regarding product profile and selection of irradiation configuration and conveyor technical capabilities and properties to optimize irradiation process.

## **Wstępne studium wykonalności instalacji radiacyjnej z wykorzystaniem wiązki elektronów, przeznaczonej do prowadzenia badań i wdrożeń**

Wiązka przyspieszonych elektronów jest powszechnie stosowana do prowadzenia badań i we wdrożeniach przemysłowych, takich jak sterylizacja wyrobów medycznych, modyfikacja izolacji w przewodach i kablach elektrycznych, modyfikacja własności polimerów czy inne technologie radiacyjne. Technologie radiacyjne mają duże znaczenie ze względu na możliwość uzyskania unikalnych własności i poprawy jakości produktów poddanych obróbce radiacyjnej. Przed rozpoczęciem prac z wykorzystaniem wiązki elektronów należy poznać techniczne i ekonomiczne parametry instalacji. Niniejszy raport przedstawia wstępne studium wykonalności instalacji radiacyjnej opracowane na podstawie oceny technologii radiacyjnej realizowanej przy wykorzystaniu czterech różnych konstrukcji akceleratorowych.

W procesie obróbki radiacyjnej zwykle jest wykorzystywany przenośnik taśmowy, który umożliwia wprowadzenie obrabianych materiałów (pojemników) w strefę oddziaływania strumienia przyspieszonych elektronów. Niekiedy stosuje się dwustronne napromieniowanie dla zwiększenia zasięgu elektronów, nawet przy wiązce o energii 10 MeV. Tego typu instalacja została zbudowana w Instytucie Chemii i Techniki Jądrowej (IChTJ) dla promocji w Polsce technologii radiacyjnych. Skonstruowany we własnym zakresie akcelerator elektronów o energii 10 MeV i mocy wiązki 10 kW charakteryzuje się efektywnością ekonomiczną i eksploatacyjną pozwalającą na jego wykorzystanie w technologiach radiacyjnych i programach badawczych. W urządzeniu tym zastosowano klistron jako źródło energii mikrofalowej o częstotliwości 3 GHz oraz sekcję przyspieszającą z falą stojącą. Analizą zostało też objęte podobne urządzenie oferowane przez firmę CORAD Company (Petersburg, Rosja).

Akceleratory rezonansowe mają jedną wnękę rezonansową pracującą z częstotliwościami rzędu 100 MHz i generatory na bazie lamp próżniowych dużej mocy. Są względnie tanie i niezawodne oraz umożliwiają uzyskanie średnich i wysokich energii elektronów przy odpowiednio dużej mocy średniej wiązki. Akceleratory typu IŁU-10 są produkowane przez Instytut Fizyki Jądrowej z Nowosybirsk (Rosja). Urządzenie to zapewnia uzyskanie energii elektronów na poziomie 5 MeV i mocy wiązki do 20 kW. Akcelerator elektronów typu Rhodotron oferowany przez firmę IBA (Belgia) został opisany jako jeden z wariantów. Akceleratory tego typu mają jedną wnękę rezonansową, którą wiązka elektronów pokonuje wielokrotnie aż do osiągnięcia energii 10 MeV. Kompaktowa konstrukcja i stosunkowo wysoka sprawność elektryczna sprawiają, że akcelerator ten jest odpowiedni do prowadzenia procesu obróbki radiacyjnej w skali przemysłowej.

Zakłada się, że instalacja radiacyjna jest eksploatowana przez 46 tygodni w ciągu roku (1840 godz./rok), ze względu na okresy świąteczne i urlopowe, a także przestoje techniczne związane z awaryjnością akceleratora. Biorąc pod uwagę pracę na jedną zmianę, straty powodowane koniecznością prowadzenia konserwacji oraz czas na załączanie i wyłączenie akceleratora, to czas jego efektywnej pracy z wiązką wynosi 1552 godz./rok. Koszty inwestycyjne i eksploatacyjne instalacji radiacyjnej zmieniają w istotny sposób zależnie od specyfikacji technicznej akceleratora i jego ceny. Wielkość mocy wiązki bezpośrednio określa wydajność instalacji, co przekłada się na poziom kosztów jednostkowych. Zmniejszenie czasu eksploatacji akceleratora z wiązką elektronów prowadzi do zwiększenia kosztów jednostkowych ze względu na rosnący udział kosztów inwestycyjnych i kosztów stałych. Szczegółowa analiza techniczno-ekonomiczna powinna zostać przeprowadzona z uwzględnieniem parametrów prowadzonej obróbki radiacyjnej określonych wymaganiami danej technologii (produktu), w celu optymalizacji procesu oraz określenia konfiguracji i technicznych możliwości transportera.

# CONTENTS

<b>1. INTRODUCTION</b>	<b>7</b>
<b>1.1. Objectives</b>	<b>7</b>
<b>1.2. Scope and limitations</b>	<b>7</b>
<b>2. TECHNICAL STUDY</b>	<b>7</b>
<b>2.1. Carton length/width</b>	<b>7</b>
<b>2.2. Scan width</b>	<b>8</b>
<b>2.3. Irradiation layout</b>	<b>8</b>
<b>2.4. Conveyor requirements</b>	<b>10</b>
<b>2.5. Process control system</b>	<b>12</b>
<b>3. ACCELERATOR SUPPLY</b>	<b>12</b>
<b>3.1. Accelerator specification</b>	<b>12</b>
<i>3.1.1. Microwave electron accelerator LAE-10/10 type</i>	<i>13</i>
<i>3.1.2. Microwave electron accelerator UELR-10-15S type</i>	<i>18</i>
<i>3.1.3. Resonance RF accelerator ILU-10 type</i>	<i>19</i>
<i>3.1.4. Accelerator Rhodotron TT100 type</i>	<i>20</i>
<i>3.1.5. Summary of accelerator specification</i>	<i>22</i>
<b>3.2. General requirements</b>	<b>22</b>
<b>3.3. Requirements for radiation protection</b>	<b>23</b>
<b>3.4. Security system</b>	<b>25</b>
<b>3.5. Radiation monitoring</b>	<b>26</b>
<b>3.6. Video control</b>	<b>26</b>
<b>3.7. Ozone extraction</b>	<b>26</b>
<b>3.8. Water cooling system</b>	<b>26</b>
<b>4. FACILITY DESIGN ASSUMPTIONS</b>	<b>27</b>
<b>4.1. Plant production capacity</b>	<b>27</b>
<b>4.2. Manpower and skills requirement</b>	<b>27</b>
<b>4.3. Location of the irradiation facility</b>	<b>28</b>
<b>4.4. Cost assessment</b>	<b>30</b>
<b>4.5. Permissions</b>	<b>33</b>
<b>4.6. Cooperation</b>	<b>34</b>
<b>5. CONCLUSIONS AND RECOMMENDATIONS</b>	<b>34</b>



# 1. INTRODUCTION

## 1.1. Objectives

Electron beam (EB) accelerators technology is now commonly accepted for research study and industrial implementation. Wide field of R&D study and business opportunities exist in electron beam accelerators facilities in various fields of applications such as sterilization for medical items, crosslinking of insulation in wires and cables, modification of properties in polymers and other radiation technologies. The importance of radiation technology is related to unique properties and quality improvement of irradiated products. Initiating work for the establishment of an electron beam facility one should recognize technical and economical parameters of the process. The facility under consideration will be implemented in the field of R&D study and may offer technical capability to introduce certain radiation technology on pilot (massive) scale. The techno-economic feasibility of irradiation process will be discussed. Specifically, technical characteristics of the irradiation process in respect to product profile are recommended and type of the facility is proposed due to volume of the products to be irradiated.

The qualification of the foundations is the main object of the present study. It allows to realize feasibility study project in connection to radiation facility dedicated to research study and practical implementation.

## 1.2. Scope and limitations

The present study reports of the assessment carried out of technical and economical feasibility for installation the facility where electron beam technology will be implemented. This study presents comprehensive technical and financial profiles of the radiation technology. As previously stated, its principal objective is to determine whether sufficient reasons exist that will sustain the feasibility of establishing facility. Presented recommendations are limited to data gathered from official documents. Essential information for electron beam processing with the production capability for the period of one year were provided. The most important facility parameters are as follows:

- electron energy: 5-10 MeV;
- beam power: 10-50 kW;
- dose range: 1-160 kGy;
- the most probable dose rate: 25 kGy;
- standard carton dimension: 580 mm × 460 mm;
- typical efficiency of beam energy transfer: 0.3;
- the price of the electrical energy: 0.32 PLN/kWh (0.1 €/kWh);
- one shift facility operation: 8 h/5 days/week;
- average currency rate (February 2018): 1 PLN = 0.24 € 1 USD = 0.8158 €

# 2. TECHNICAL STUDY

## 2.1. Carton length/width

Radiation processing is usually based on moving conveyor and scanned electron beam which provides possibility to irradiate cartons containing modified (or sterilized) products. It should be noticed that usually carton length refers to the dimension parallel to the direction of the conveyor movement during irradiation process. In respect to that the carton width refers to the dimension perpendicular to the direction of movement when the box is under the beam.

According to initial data the standard carton dimension is found to be 580 mm × 460 mm. The vertical dimension of the carton will depend on product density and electron energy level.

It should be noticed that two- and sometime four-sided irradiation is applied for certain product dimensions at electron energy range 10 MeV. The maximum box length is proposed to be 120 cm. The one carton weight can vary but the maximum value of surface product density for one-sided irradiation should not exceed 2.5 g/cm<sup>2</sup> for optimal dose homogeneity during radiation sterilization process.

## 2.2. Scan width

Width of scanned electron beam forms irradiation zone in the direction of the beam sweeping which is located perpendicularly to the product movement. Electron beam is driven by the current of the scan electromagnet according to its time characteristic. The irradiation zone dimension is directly related to electron beam scan width (SW; beam path length) in so-called linear scanning system. It depends on accelerator specification (exit window length) of certain accelerator construction. Accelerator producer usually can provide the beam scanner with required exit window length on special order.

The other option is related to additional electromagnet system which provides capability of so-called “parallel beam” after exit window. It slightly reduces electron beam losses and improves homogeneity of irradiation process.

Uniformity of the product irradiation should be evaluated according to scanning linearity (inhomogeneity of the beam current density along the window length; usually ±10%), instability of the beam current (usually ±2.5%), frequency of scanning signal and conveyor width and speed.

## 2.3. Irradiation layout

The typical irradiation layout in contract irradiation facilities with conveyor is presented in Fig. 1. The scan width is usually higher than carton box width (BW) what leads to extra electron beam losses. Typical accelerator construction usually allows to correct scan width by simple adjustment of current level in scanning electromagnet. In such case beam utilization coefficient will be improved but at the same time conveyor system should be adopted to keep the carton in center position regarding scanning device and conveyor.

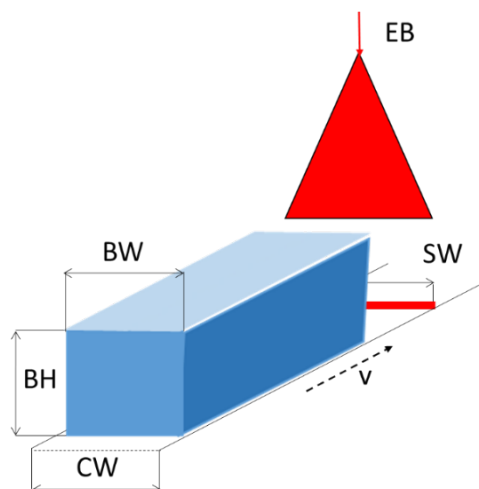


Fig. 1. Typical geometry of irradiation process performed in accelerator facility with conveyor as under beam equipment: EB – electron beam, CW – conveyor width, SW – scan width, BW – carton box width, BH – carton box height, v – conveyor speed. Carton box maximum cross-section (BW × BH) 480 mm × 400 mm



In particular case (maximum cross-section 460 mm × 400 mm) suitable distance between conveyor surface and accelerator window is required. When that distance is higher than necessary one can expect higher ozone production rate and some extra beam energy losses in air path.

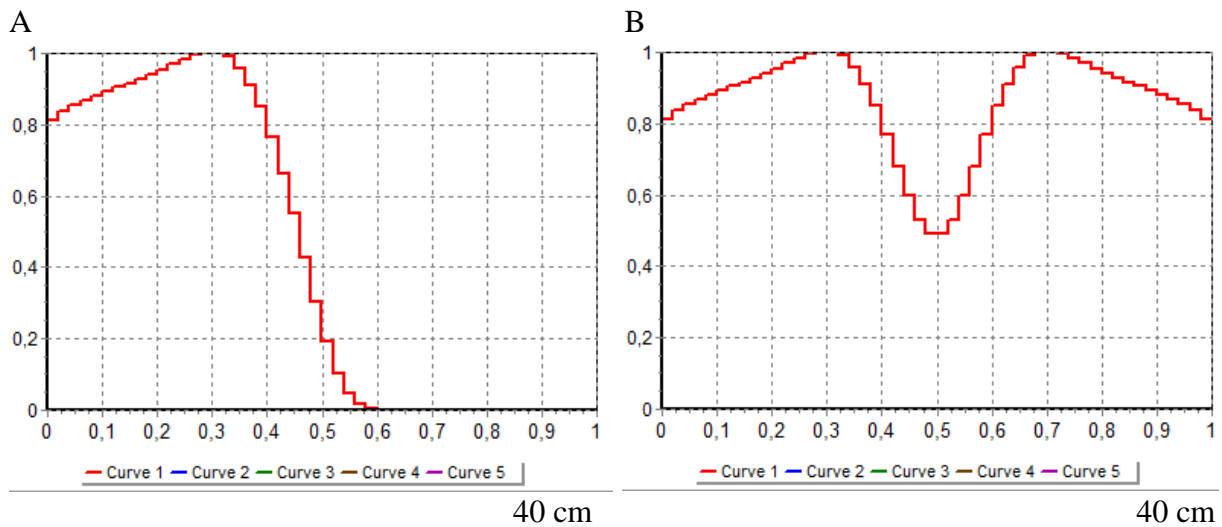


Fig. 2. Depth dose distribution in homogeneous object with unit density 0.25 g/cm<sup>3</sup> and thickness 40 cm irradiated by scanned electron beam with energy 10 MeV for: A – one-sided irradiation, B – two-sided irradiation

One of the most important parameter is the dose homogeneity within the irradiated product. Due to product higher density two-sided irradiation is necessary. The penetration range of accelerated electrons depends mostly on electron energy level, product geometry and its density. Figures 2 and 3 show calculated depth dose distribution within irradiated box with dimension 460 mm × 400 mm, product density 0.22-0.25 g/cm<sup>3</sup>, for electron energy 10 MeV and 5 MeV when one- or two-sided irradiations are applied.

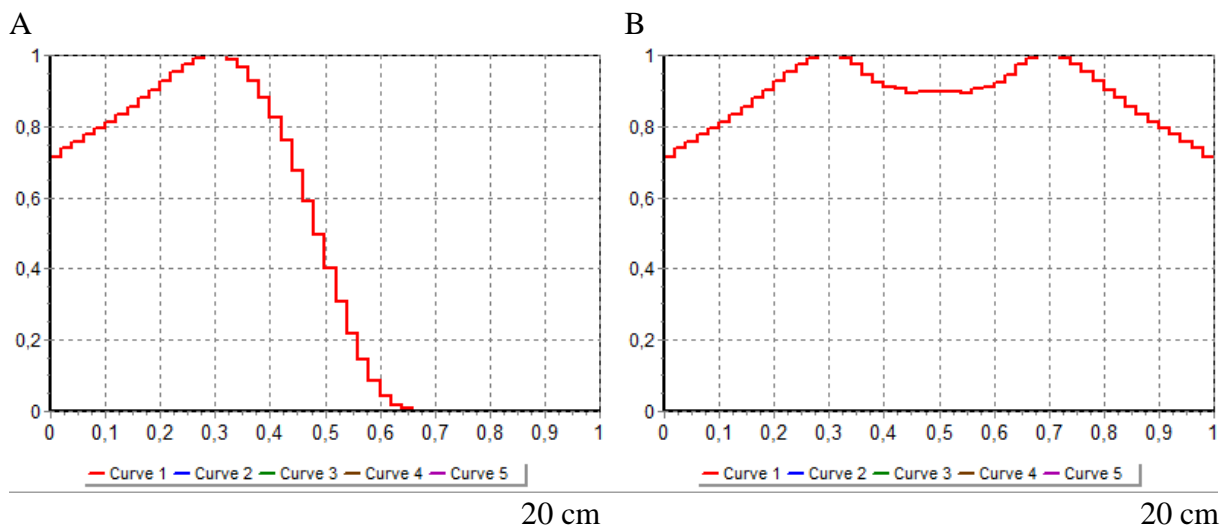


Fig. 3. Depth dose distribution in homogeneous object with unit density 0.22 g/cm<sup>3</sup> and thickness 20 cm irradiated by scanned electron beam with energy 5 MeV for: A – one-sided irradiation, B – two-sided irradiation

The computer simulations of circumferential dose distribution initiated by scanned electron beam in flat irradiated material were performed by Monte Carlo method with utilization of the software program ModeRTL described in the IAEA publication (Lazurik, V.T., Lazurik, V.M., Popov, G., Rogov, Yu., & Zimek, Z. (2011). *Information System and Software for Quality*

*Control of Radiation Processing*. Warszawa). The computer program ModeRTL was designed specifically for simulation dose distribution in multilayer circular objects for the electron energy range 0.1-25 MeV. The self-consistent physical and geometrical models of the program ModeRTL include features of electron beam transport and the dose field formation in circular objects. The program ModeRTL uses as input data number of parameters related to radiation facility including electron beam spatial distribution and material properties and dimensions. The verification of simulation results was performed by dosimetry experiments.

As can be easily noticed, one- and two-sided irradiations are acceptable with defined homogeneity of depth dose distribution for exact relation between electron energy and product density and thickness.

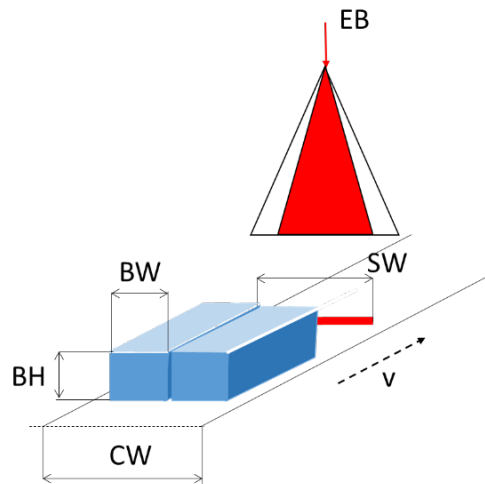


Fig. 4. Geometry of irradiation process performed in accelerator facility with conveyor as under beam equipment: EB – electron beam; CW – conveyor width, SW – scan width, BW – carton box width, BH – carton box height,  $v$  – conveyor speed. Carton box maximum cross-section ( $BW \times BH$ ) 250 mm  $\times$  250 mm

As mentioned before, typical accelerator construction usually allows to correct scan width by simple adjustment current level in scanning electromagnet to reduce beam power losses (Fig. 4). In such case beam utilization coefficient will be improved but at the same time conveyor system should be adopted to keep the boxes in center position regarding scanning device.

## 2.4. Conveyor requirements

The conveyor shall carry cartons from the loading area to the irradiation process zone which is located inside the concrete shelter. The products should be processed at a specified speed by scanned electron beam usually coming from the top. After being irradiated, the cartons should leave the shelter.

The conveyor is divided into different subsections in order to ensure a smooth, bump free and continuous product movement under the beam. Everywhere on the conveyor, the cartons should be correctly guided avoiding any transportation disturbance such as skidding, blocking or turning head to tail. The material to be irradiated may be contained in cartons of various sizes.

The whole system should be fully controlled and driven by a PLC with its associated control features. At the vicinity of the beam, the environment will be very corrosive; stainless steel is to be used for construction of the irradiation process conveyor. Plastic parts, electronic and electric devices should not be present close to irradiation zone.

The conveyor necessary for implementation of irradiation process can be provided by accelerator manufacturer or accelerator manufacturer can recommend certain company with suitable experience in that field. It is also possible design conveyor construction based on typical components accessible on the market supported by unique mechanical equipment specifically matched to certain product and selected configuration of irradiation process.

Mechanical and electrical hazards exist during conveyor use. The supplier shall analyze the associated risks and provide appropriate guards and interlocks against such hazards. Figure 5 shows typical conveyor system for carton irradiation process composed of different segments.

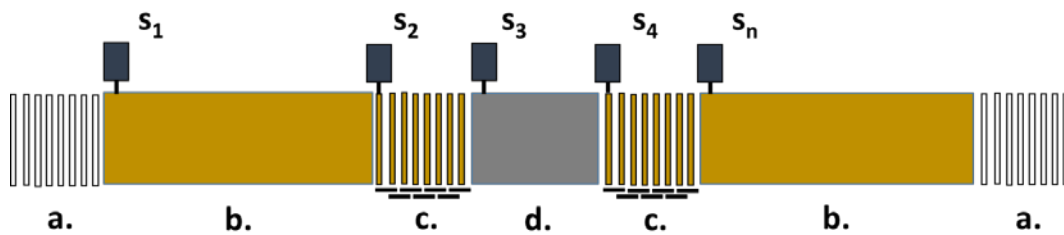


Fig. 5. Typical conveyor system for cartons irradiation process composed of different segments: a – rolls, b – belt conveyor, c – roll conveyor, d – conveyor with speed control located in irradiation zone, s – individual engine of the conveyor segment

Figure 6 shows typical conveyor bends necessary in conveyor lay out due to existence of the labyrinth through shielding walls of facility shelter. The key role of the conveyor system plays conveyor segment with speed control located in irradiation zone. Its speed should be precisely adjusted according to beam current and required dose level. Stable conveyor movement assures stable dose level. The feedback loop to beam current sensor allows to automatically compensate beam instability by conveyor speed variation to keep dose rate constant. All conveyor components located inside irradiation chamber should be protected against radiation to avoid corrosion caused by ozone presence. The belt made of stainless steel wires or rollers type conveyor are frequently used to transport irradiated product under exit window.

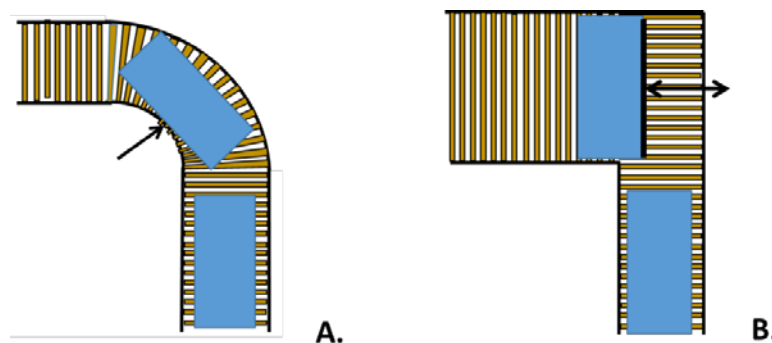


Fig. 6. Typical conveyor bends necessary in conveyor lay out due to existence of the labyrinth through shielding walls of facility shelter

Manual loading and unloading rolling lines with accumulation buffer action should be located at the beginning and at the end of conveyor. The number of other specific segments could be recognized depending on the conveyor configuration and complexity. These include:

- entrance conveyor with elevator section to a superior level / lowering conveyor to ground level;
- accumulation area before irradiation section to eliminate gaps between cartons;
- option to 180° flipping over section second irradiation loop (flipping over station receives the cartons which have already been irradiated once);
- special guiding for the twin cartons. This system is used to inject the cartons at the entrance of the irradiation loop. To ensure a final throughput within the specification, the cartons should be grouped. So the cartons can be driven two by two (or one by one).

During irradiation tubes or pips several product turns can be finalized to obtain necessary dose homogeneity. It is possible in advance preparation the trolley with certain tubes dimensions. The special mechanism providing necessary tube rotation should be applied for different tubes dimensions and thickness.

## **2.5. Process control system**

The whole process should be controlled both by process control system (PCS) which will confirm that the irradiation takes place with the good parameters and a real time. The PCS should continuously measure the key parameters of the beam and conveyor (beam intensity, scan length and conveyor speed). At the end of the batch process it should be possible to issue an irradiation certificate.

### Conveyor control system

The conveyor should carry through the irradiation process the products packaged in cartons that need to be modified by electron beam. Each carton should be irradiated from one or two sides with 180° flip over movement according to specification. The whole system should be usually designed to work 24 h a day and 5 days a week. The cartons are loaded on the conveyor at a manual loading station. The main different sections of the conveyor are as follows:

- manual loading / unloading lines with accumulation buffer action,
- entrance conveyor with elevator / lowering sections to a superior level / ground level,
- accumulation area before irradiation section,
- irradiation stainless steel conveyor able to drive each box within specification under the beam,
- 180° flipping over section second irradiation loop,
- special guiding for the twin cartons.

So-called under beam conveyor is directly under the beam. The speed should be fully controlled by a supplementary device. The tolerance should be around  $\pm 1\%$ . The structure of this conveyor is in stainless steel and the absence of other elements is of course applicable to the whole area. The cartons should be introduced on the irradiation conveyor close to one another without bumping. Conveyor control system (CCS) including program and control features should be provided by the conveyor supplier. It should be coordinated with PCS responsible for accelerator operation. Automatic stop of the conveyor should take place when electron beam disappear suddenly due to technical reasons. Automatic electron beam stop should take place when conveyor is suddenly stopped due to technical reasons.

### Monitoring control system

Monitoring control system can be provided by accelerator manufacturer for independent supervision of the irradiation parameters.

### Dosimetry system

The dosimetry system should be selected and purchased to read certain film dosimeter (B3, Gex, FW, CTA) with adequate devices integrated with the UV-Vis spectrophotometer. The following items are also recommended: aluminum wedge, calibration filters thickness gauge, reference thickness blocks, PC with dosimetric program, printer.

## **3. ACCELERATOR SUPPLY**

### **3.1. Accelerator specification**

Accelerator is the key device of any electron beam radiation facility. It is responsible for productivity of the process and economical effects of the applied radiation technology. The energy of accelerated electrons determines their penetration into the irradiated material, what determines the geometry of the irradiation process. Sufficient average power of the beam of electrons ensures achievement of the required capacity of the process, costs minimization, and should be accessible for continuously operating installation. Differences between various types of accelerators mainly come down to the difference in the generation of electric field which is used to accelerate the electrons. Two basic ways of generating accelerating voltage are used in accelerators applied for radiation processing:

- high voltage power supplies (transformer accelerators, low energy level),

- radio- and microwave frequency generators for accelerators where the electric component of electromagnetic wave is used in the process of electrons accelerating (resonance accelerators with single accelerating gap and multi-cavity high frequency linacs, high energy level).

The process of accelerating electrons takes place in the vacuum inside of accelerating section where cathode emitting electrons is installed in one side, while the system for transporting and conveying of the beam through output foil (scanner) is installed in other side.

Industrial irradiation processes using high-power electron accelerators are attractive because the throughput rates are very high and the treatment costs per unit of product are often competitive with more conventional chemical processes. The utilization of energy in electron beam processing is more efficient than typical thermal processing.

The principle of certain accelerator operation is based on difference in electric field generation, related to this accelerating section construction and the accelerated particles trajectory shape. Four accelerator constructions are described as an interesting technical solution: two microwave resonance accelerators in which the electric component of electromagnetic wave accelerates electrons in number small resonance cavities and two RF accelerators with single cavity resonator each.

High energy scanned beam systems driven by RF sources are capable of providing from 5 to 700 kW average beam power at electron energy range 5-10 MeV. They are used for medical product sterilization and crosslinking and polymerization of even thicker materials. Microwave linacs provide electron beams with energy 10 MeV and beam power up to 100 kW.

Fundamental accelerator parameters: electron energy and average beam power define technological abilities and facility productivity. Although there are many different types of accelerators offering a wide range of performances ratings, only a few would be suitable for particular application.

### 3.1.1. Microwave electron accelerator LAE-10/10 type

Radiation facility located at the Institute of Nuclear Chemistry and Technology (INCT, Warszawa, Poland) has been build, towards higher technical and economical effectiveness, better operational characteristics suitable for radiation processing and research programs in order to promote in Poland the radiation processing technologies including sterilization medical devices and tissue grafts and other radiation processes where high energy electrons are required. The objective of the project was 10 MeV, 10 kW linear electron accelerator equipped with microwave source based on modern klystron device TH2158 operated at frequency 2856 MHz and standing wave accelerating section.

The following accelerator components have been tested in final stage: water cooling system, vacuum system, electron gun and dun modulator, microwave system of accelerator including pulse power supply, beam scanning system and control system. The klystron modulator was designed based on high power semiconductor HV transistor. Electron beam alignment, beam parameters evaluation and accelerator commissioning are being performed during commissioning stage. The better accelerator availability, more stable beam parameters, better spare parts availability, reduced exploitation costs and higher beam power are expected after successful accelerator implementation in radiation processing.

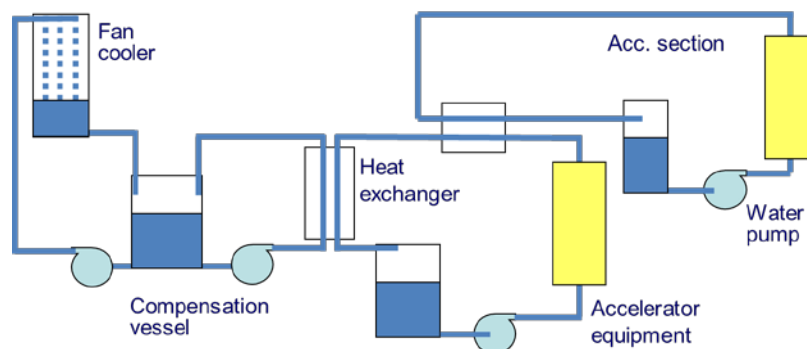


Fig. 7. Accelerator close loops water cooling systems

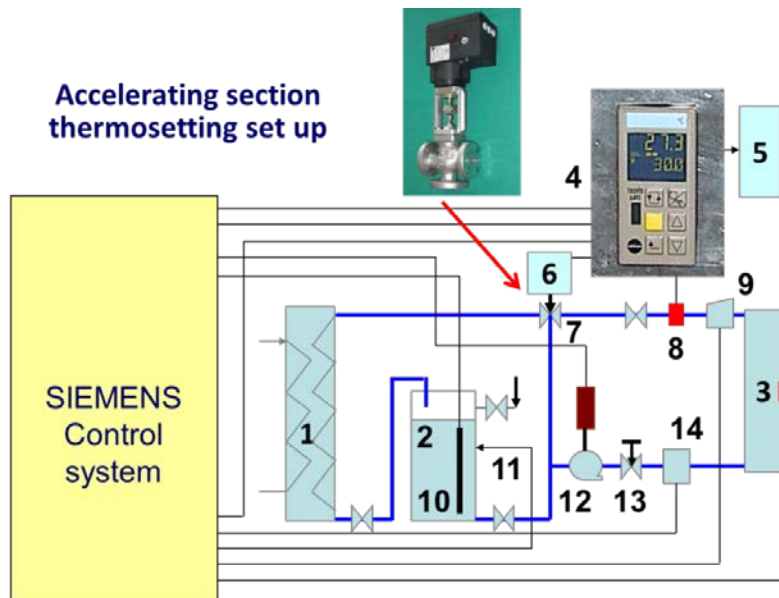


Fig. 8. The configuration of water loop with temperature stabilization: 1 – heat exchanger, 2 – compensation vessel, 3 – accelerating section, 4 – microprocessor, 5 – control signal, 6 – driver, 7 – three-way valve, 8 – temperature sensor, 9 – flow rate sensor, 10 – heater, 11 – level sensor, 12 – water pump, 13 – valve, 14 – pressure sensor, 15 – temperature sensor

Accelerator water cooling system consists of three close loop subsystems as can be seen in Fig. 7. Outside cooling loop filled up with ordinary water consists of fan cooler, compensation vessel, heat exchanger and two water pumps. Fan cooler can be located on the roof of the building. The inside cooling loop consists of heat exchanger, compensation vessel and all accelerator equipment required to be cooled down.

The third loop subsystem is filled up with distilled water and consists of heat exchanger, compensation vessel, water pump and accelerating section. The primary task of that subsystem is accelerator section temperature stabilization on certain level. It can be obtained due to application of three-way valve operated by dedicated microprocessor. The configuration of water loop with temperature stabilization is shown in Fig. 8.

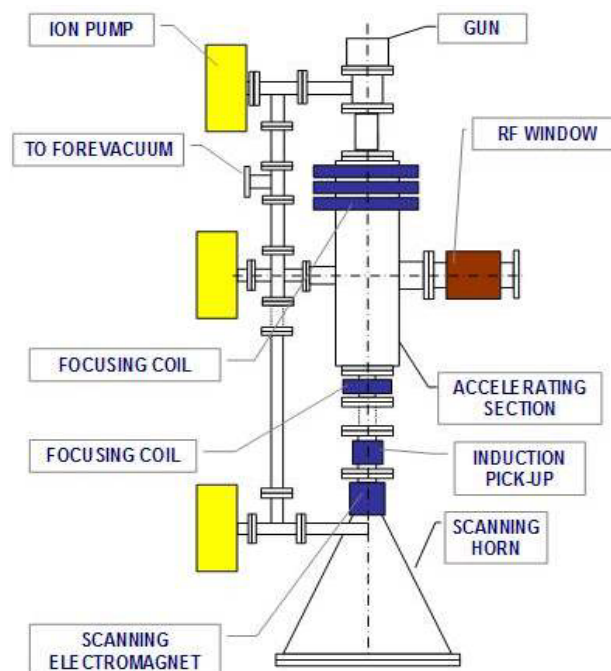


Fig. 9. The block diagram of accelerator LAE-10/10 vacuum system

The accelerator LAE-10/10 vacuum system consists of three ion vacuum pump type HMDI-0,063 (pumping velocity 60 l/s) with power supply BPM-0,25 (Fig. 9). Turbomolecular pump is used to start ion pumps at certain vacuum level.

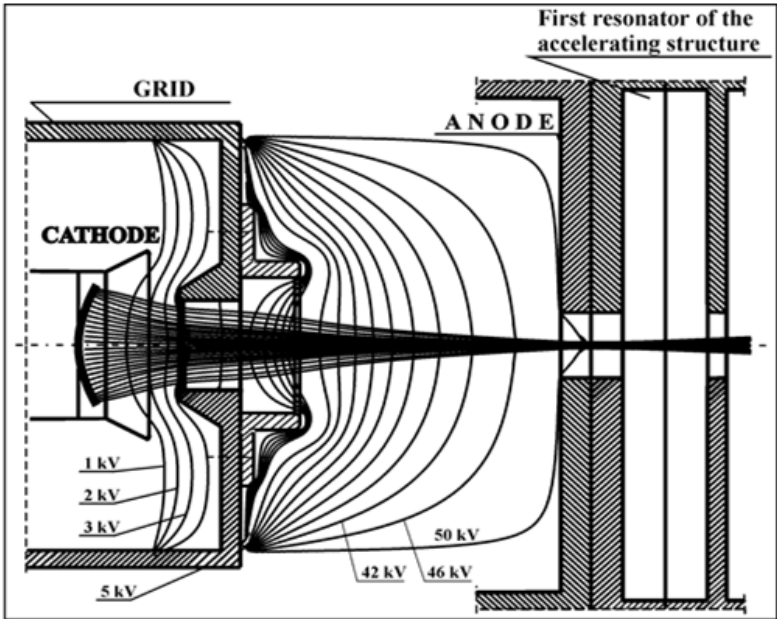


Fig. 10. Electron gun structure with voltage equipotential lines and electron trajectories

The electron gun parameters (pulse current, voltage) should be compatible with electrical specification of the accelerating structure. The triode electron gun with spherical impregnated cathode (manufacturer “Toriy” company) is used as a source of electrons in accelerator LAE-10/10. Electron gun construction meets requirements of standing wave structure applied in accelerator and provides desirable shape of the electron beam what is shown in Fig. 10. Shapes of the equipotential lines are congenial to actual shapes of the lines in the electron beam area, but the lines differ from actual far from the area. It is due to accepted mathematical model. The following gun optimization was necessary to meet requirements of standing wave structure applied in accelerator: distance between cathode and grid, distance between grid and anode, beam focusing to obtain proper beam dimensions.

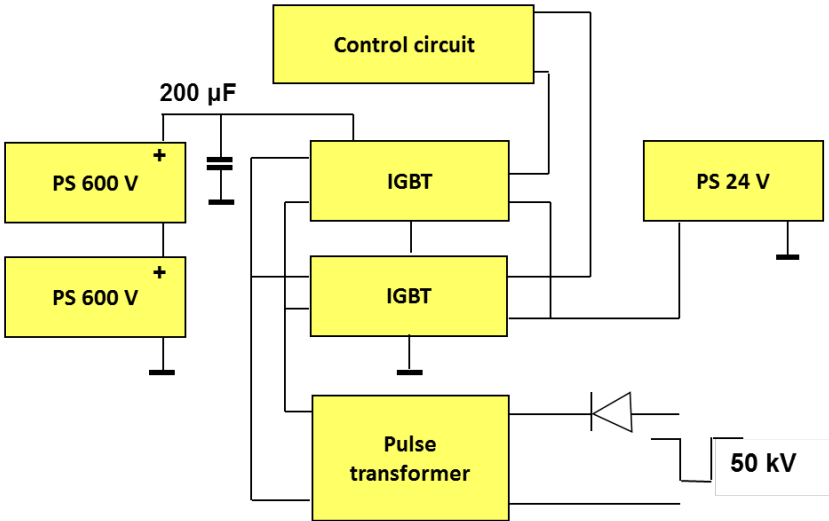


Fig. 11. Block diagram of electron gun modulator

The electron gun modulator unit which block diagram is presented in Fig. 11 provides pulses with amplitude 50 kV and duration up to 20 μs. The modulator can be operated with the

following parameters: frequency 330 Hz, average current 2 mA, maximum pulse current 1.3 A, interface RS 232.

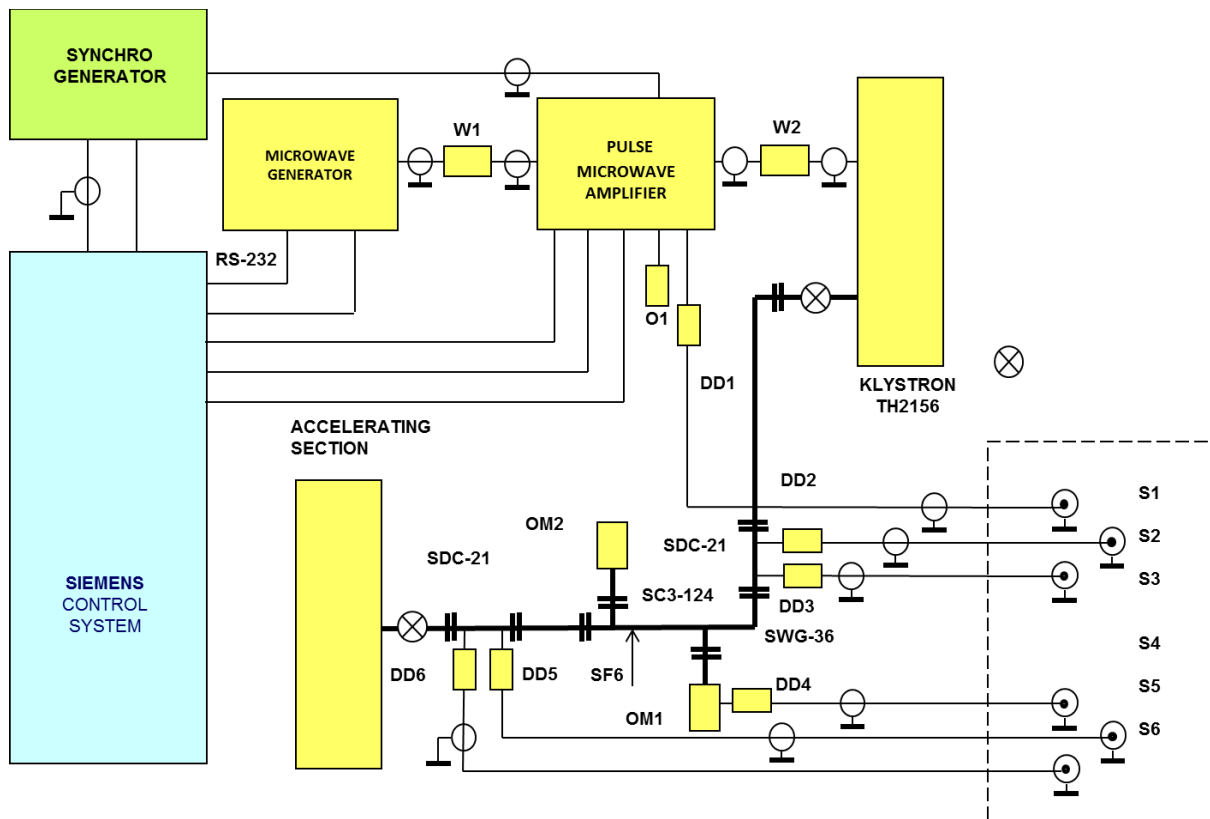


Fig. 12. The block diagram of accelerator LAE-10/10 microwave system: O1 – 50 Ω load, OM1 – microwave load, DD1 – diode, SDC21 – directional coupler, SWG36 – E plane bend, SC3-124 – isolator

The main microwave system of the accelerator is composed of the following components: klystron TH 2158, waveguides and accelerator section. Additional subsystem composed of microwave generator and pulse amplifier is used to provide necessary microwave signal on klystron input. Pulse microwave amplifier type AM82-2,85S-43-53R was applied with frequency  $2856 \text{ MHz} \pm 10 \text{ MHz}$ , output pulse power 53 dBm, amplification factor 43 dBm. The block diagram of accelerator LAE-10/10 microwave system is shown in Fig. 12.

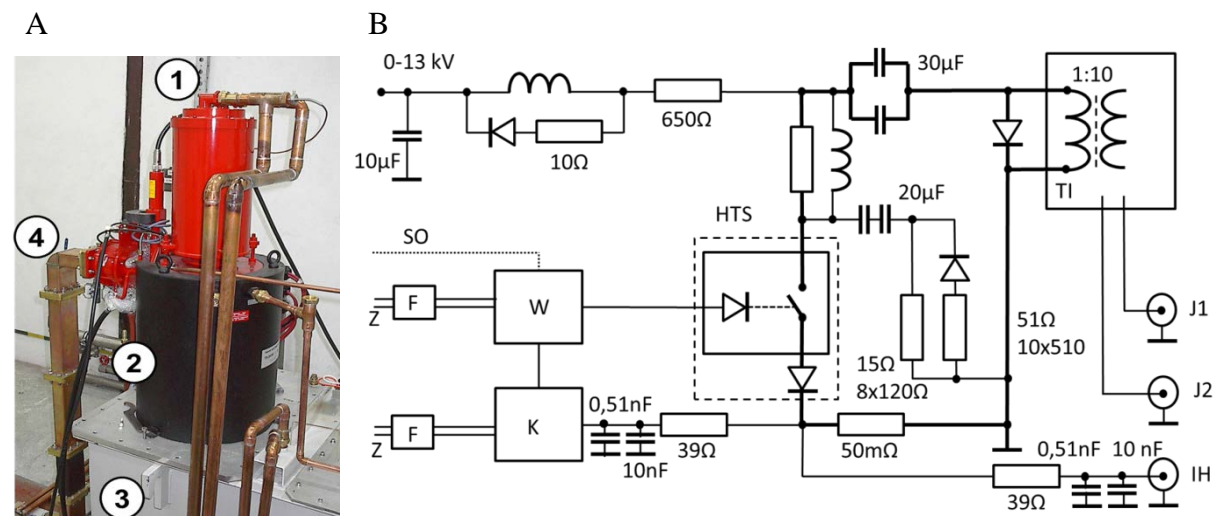


Fig. 13. Klystron modulator: A – klystron type TH 2158 (1 – klystron TH-2158, 2 – focusing coil, 3 – HV pulse transformer, 4 – waveguide), B – modulator principal diagram



High voltage, pulse modulator was designed and constructed to provide pulses with amplitude up to 135 kV, duration 20  $\mu$ s and repetition rate up to 330 Hz. The partly discharged capacitor bank is applied and semiconductor switch is used to form certain pulse time structure. The klystron TH-2158 (modulator load device) is supplied by HV pulse through 1:10 pulse transformer. Klystron modulator is based on semiconductor switch HTS 181-160 FI (acceptable current load 1600 A, with voltage up to 18 kV). The modulator is equipped with safety (shutdown) circuit for protection against current overload which may appear. The klystron and principal diagram of modulator are displayed in Fig. 13.

Accelerator LAE-10/10 output device consists of output chamber with titanium foil 50  $\mu$ m thick, vacuum pump and scanning electromagnet (Fig. 14).

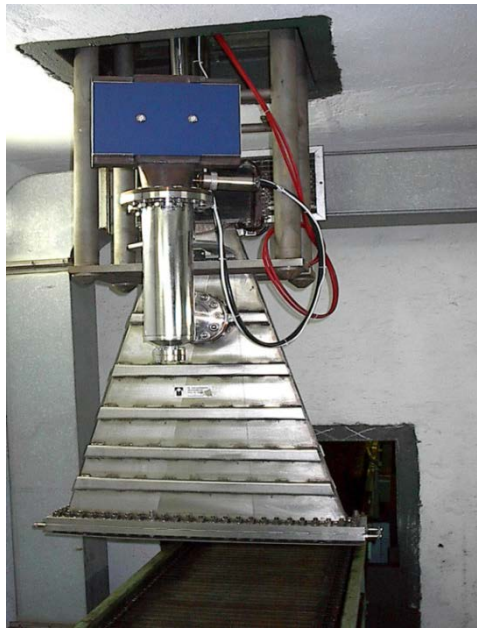


Fig. 14. Accelerator LAE-10/10 output device

Accelerator control system is located in control panel unit (Fig. 15). It is equipped with Siemens microprocessors and modules type Simatic S7-300, with communication channel Profibus and as SCADA tool (Supervisory Control And Data Acquisition) WinCC. The control



Fig. 15. Control panel with fuse and breaker unit, connection unit, and microprocessor and interface module units

system consists of: PS – power supply, CPU – microprocessor, IM – interface module, SM – analog and digital input/output modules, FM – functional counter module, ET 200 S – extension unit to RS232 interfaces, MP 370 – touch panel. Control system is responsible for switching on and off all independent units, safety interlock, starting up and down procedures, automatic parameters measurements. The touch panel screens are shown as an example of switching on and off procedures, and control klystron HV modulator with safety interlock announcement controlled by microprocessor.

Table. 1. Nominal parameters of linear accelerator LAE-10/10

Nominal parameters	Value
Electron energy (nominal)	10 MeV
Average beam power	10 kW
Pulse beam current (nominal)	0.3 A
Pulse current change	0.2-0.5 A
Pulse duration (nominal)	20 $\mu$ s
Pulse duration change	2-20 $\mu$ s
Repetition frequency (maximum)	330 Hz
Repetition frequency change	10-330 Hz
Average beam current (nominal)	1.0-1.3 mA
Average beam current change	0.05-1.3 mA
Scan width (nominal)	60 cm
Scan frequency	5-15 Hz
Scan width change	20-60 cm

Nominal parameters of linear accelerator LAE-10/10 constructed at the INCT are as follows: electron energy 10 MeV, beam power 10 kW (Table 1). Advantages of the developed accelerator over the accelerator already installed at the Institute facility are related to: more stable accelerator exploitation, lower exploitation costs, higher accelerator availability obtained with moderate cost. Accelerator is equipped with standing wave accelerating section (NIIEFA, Russia), and supplied by klystron TH 2158 (Thales, France). Basic components of microwave route in addition to accelerating section and klystron are continuous wave microwave generator, microwave pulse amplifier and microwave waveguide. The range of work was performed during starting up of accelerator LAE-10/15 and testing, measurements and calibrations as the part of initiated accelerator commissioning procedure.

### 3.1.2. Microwave electron accelerator UELR-10-15S type

The main feature of linear microwave accelerator is the microwave energy source use in electron accelerating process. Power supplies consist of microwave generators mainly in S-band frequencies (3 GHz). A large number of small resonant cavities are used. Microwave source parameters (price, life time) play a crucial role in implementation of linacs of this type.

The klystrons are more stable in frequency and power but they have efficiency of 40-50% in comparison with 70% efficiency of magnetrons which lifetime is significantly lower. Microwave linacs can be built with traveling or standing wave configuration. Radiation facility with linac (Fig. 16) offered by CORAD Company (Saint Petersburg, Russia) is designed for installation inside of industrial buildings or warehouses. Accelerator UELR-10-15S has following basic technical characteristics:

- electron energy: 10 MeV;
- maximum beam power: 15 kW;
- maximum pulse amplitude of the electron beam current: 0.25 A;
- pulse repetition rate: 1, 3.06, 6.125, 12.5, 25, 50, 100, 200, 400 Hz;
- electron beam pulse duration: 0.015 ms;
- maximum scan length: 700 mm;
- maximum power consumption: 110 kW;
- homogeneity of dose along the scan length on both sides of irradiated boxes:  $\pm 5\%$ ;
- beam power stability:  $\pm 2.5\%$ ;
- electron energy stability:  $\pm 2.5\%$ ;
- the accelerator supplied from three-phase networks 380/220 V, 50 Hz, with the isolated neutral wire, stability:  $\pm 5\%$ .

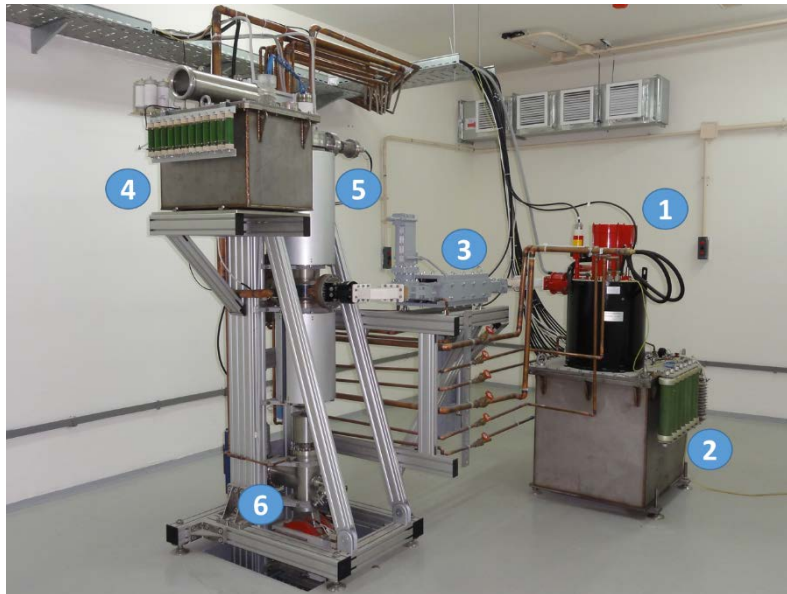


Fig. 16. Microwave linear electron accelerator UELR-10-15 type: 1 – klystron, 2 – pulse modulator, 3 – microwave circulator, 4 – gun modulator, 5 – accelerating section, 6 – scanner

The external water circuit of cooling (not included in the delivery kit) should dissipate power of 90 kW and provide following condition in the output: water temperature of cooling no more than 25°C, water flow for 25°C – 120 l/min. The basic features of accelerator are the following:

- high efficiency solid-state modulators for klystron and electron gun with DC voltage less 800 V on the basis of thyristors;
- continuous control of electron energy, scan length and beam current during electron beam processing.

During an operation of the accelerator periodic replacement of the klystron and the cathode of the electron gun is required.

### 3.1.3. Resonance RF accelerator ILU-10 type

Resonant HF accelerators are based on the large resonant cavities working at the frequency varying from one to several hundred MHz. Those cheap and reliable components require relatively simply and compact DC or pulse modulators to generate HF oscillations. Medium and high electron energy level with appropriate beam power can be obtained.

The first industrial accelerators of this type were developed at the Institute of Nuclear Physics (INF, Novosibirsk, Russia). ILU type electron accelerators are based on one coaxial resonator operating in pulse regime (Fig. 17). Industrial model of HF resonant accelerator was developed to cover energy range from 0.5 up to 5 MeV with average beam power up to 50 kW. Above 50 accelerators ILU type were constructed and installed in Russia and several other

countries for different field of R&D and industrial applications. Main parameters of operation regime ILU-10 accelerator are as follows:

- energy: 4-5 MeV,
- average current: 0-10 mA,
- average beam power: up to 50 kW,
- pulse current: 0-400 mA,
- pulse duration: 0.5 ms,
- pulse repetition: 1-50 Hz,
- RF frequency: 115 MHz,
- dimensions: Ø1280 mm × 1480 mm.

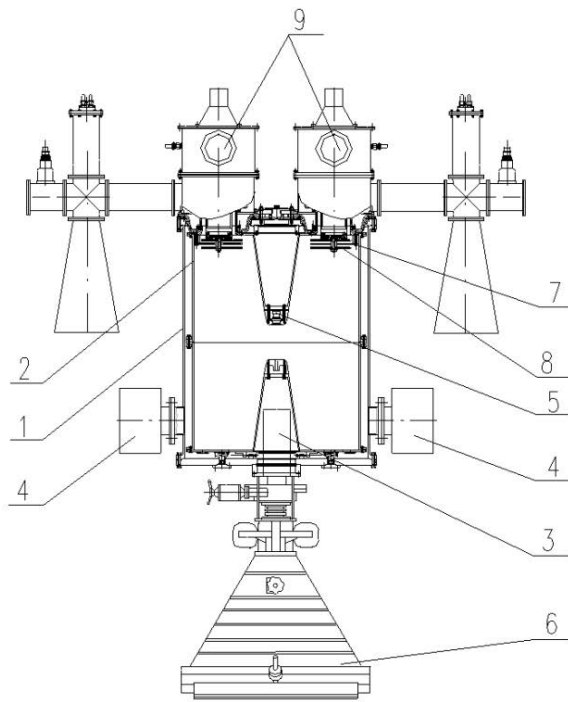


Fig. 17. RF electron accelerator type ILU-10: 1 – vacuum envelope, 2 – resonator, 3 – focusing coil, 4 – ion pump, 5 – electron gun, 6 – scanner, 7 – coupling loop support, 8 – vacuum capacitor, 9 – RF generators

ILU type electron accelerator family is represented by several constructions with different electron beam parameter. The units suitable for this application are listed in Table 2.

Table 2. ILU type accelerator family

Parameter	Accelerator type	
	ILU-10	ILU-10 M
Electron energy	4-5 MeV	4.5 MeV
Beam power	up to 50 kW	10 kW*

\* The accelerator ILU-10 M can be upgraded to ILU-10 configuration

### 3.1.4. Accelerator Rhodotron TT100 type

Rhodotron type electron accelerators presented in Fig. 18 are based on relatively new concept of electron accelerator arrangement. Family of Rhodotron accelerators were developed by IBA Company (Belgium). Using multipass system across resonant cavity 5-10 MeV electron energy and up to 700 kW beam power can be obtained.

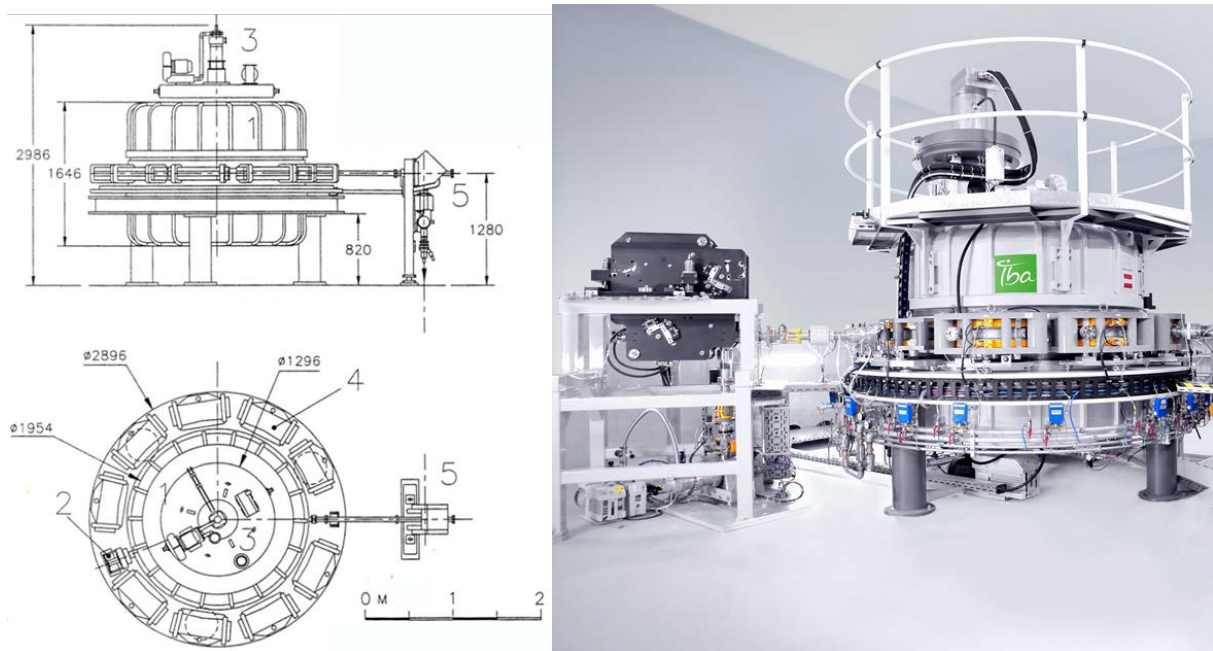


Fig. 18. RF electron accelerator Rhodotron TT200 type: 1 – vacuum envelope, 2 – electron gun, 3 – RF tetrode amplifier, 4 – deflecting electromagnet, 5 – bending electromagnet

The concept of HF electron accelerator arrangement as Rhodotron was invented in France. The coaxial line short-circuited on both ends was proposed to accelerate electrons in standing wave conditions. The electric field is radial with maximum at the median plane whereas the magnetic field is azimuthal and is equal to zero at the median position. That creates opportunity to accelerate electron beam crossing diametrically the cavity without distortion coming from magnetic field presence. Bending devices located outside of cavity are used to successive beam acceleration in the same electric field. There is continuous beam operation with RF modulation of the electron intensity. Accelerator is characterized as continuous beam operation device but with RF modulation of the electron intensity. The compact construction, relatively high (up to 50% of electrical efficiency) high energy and high beam power make this accelerator suitable for industrial application. Accelerators of this type can be easily upgraded by installing additional modules to increase average beam power. Rhodotron accelerator family includes several models: TT100 (10 MeV, 40 kW), TT200 (10 MeV, 100 kW), TT300 (10 MeV, 245 kW), TT1000 (7 MeV, 560 kW). Second generations of Rhodotron type accelerators is offered since 2018. Rhodotron TT100 model is recognized as compact accelerator with the following parameters:

- electron energy: 3-10 MeV,
- electron energy spread: less than 0.3 MeV,
- maximum beam power: 40 kW,
- beam current stability: better than 0.5%,
- full diameter: 1.6 m,
- full height: 1.75 m,
- weight: 2.5 t,
- number of passes: 12,
- energy gain per pass: 0.833 MeV,
- electrical efficiency: 20%,
- maximum line power: 210 kW.

As an option, Rhodotron can be supplied with a two-staged scan horn system that delivers a scanned but not-diverging (parallel) beam. Beam scan length can be varied from 30 to 100%. Electron beam can be scanned with frequency 100 Hz (optionally 200 Hz).

### 3.1.5. Summary of accelerator specification

Table 3 shows the basic physical parameters related electron accelerators capable to be established in facility for radiation processing. The presented units with certain physical charac-

Table 3. Electron accelerators for facility used for radiation processing

Energy	High energy	High energy	Medium energy	High energy
Accelerator type	LAE-10/10	UELR-10-15S	ILU-10	TT100
Producer	INCT	CORAD, Russia	INP, Russia	IBA, Belgium
Energy	10 MeV	10 MeV	5 MeV	10 MeV
Power source	klystron	klystron	pulse triode	tetrode
Beam current	0.1-1 mA	1.5 mA	10 mA	4 mA
Beam power	10 kW	15 kW	50 kW	40 kW
Power consumption	125 kW	150 kW	200 kW	210 kW
	150 kW (overall)	175 kW	225 kW	235 kW
Energy efficiency	10%	10%	25%	20%
Window size	600 mm	600 mm	800 mm	800 mm
Shield thickness	3 m	2.5 m	2.5 m	3 m

teristics referring to electron energy and beam power as well as economical data (Table 4) can be compared to optimize investment process.

Table 4. Delivery conditions

Energy	High energy	High energy	Medium energy	High energy
Accelerator type	LAE-10/10	UELR-10-15S	ILU-10	TT100
Delivery time	-	12 months	12 months	-
Transport	-	1 month	2 months	-
Installation	-	4 months	4 months	-
Maintenance	difficult	difficult	moderate	difficult
Main spare part	klystron	klystron	triode	tetrode
Main advantages	high energy	high energy	compact construction	high energy
Main disadvantages	low EB power, low electrical efficiency, high operation cost	low EB power, low electrical efficiency, high operation cost	-	high operation cost
Conveyor (as option)	-	yes	-	yes

## 3.2. General requirements

General requirements are related to accelerator rooms, accelerator equipment location, accelerator electric and water power supply, rooms ventilation, elevating mechanism.

### Power line

Power line voltage with three phases 380/220 V  $\pm 10\%$  and frequency 50 Hz is required. *Note.* In some cases it is recommended to use a separate transformer with nominal parameters. Consumed power by accelerator unit is up to 210 kW (depends on accelerator type).

In some cases it is recommended to connect the accelerator to the power line through a device providing a visible disconnection in the power supply circuit when the voltage is switched off. The accelerator equipment must have a separate grounding. Power and control-measuring cables should be put into a separate cable trench or separate routs.

### Environment

Typically the temperature in the range  $+10\div+35^{\circ}\text{C}$  and humidity no more than 90% at a temperature  $+25^{\circ}\text{C}$  are required in respect to accelerator equipment.

### Ventilation

General ventilation with a suitable capacity should be installed. It is recommended (to reduce ozone propagation) to confine the beam damping zone by an aluminum or stainless steel screen 4-5 mm thick. The air should be exhausted from zone where electron beam is deposited into irradiated material.

*Note.* The air line of the ventilation system must be made of aluminum or stainless steel.

Accelerator chamber (irradiation room) should be equipped with the inflow-exhaustive or only exhaustive ventilation systems for air radiolysis products (ozone and nitrogen oxides) removing. Ventilation system productivity should provide the air exchange multiplicity in accordance with local sanitary rules.

An important feature of supply ventilation is a certain balance of air in the room containing accelerator scanner and irradiation zone. Air should be supplied at such a rate, as to ensure that the pressure in this room is lower than those prevailing in the neighboring rooms. This will prevent the ozone from getting out of the accelerator building.

The exhaust and supply ventilation system in other rooms, where accelerator devices are operating, should be designed in such way as to make proper provisions for the balance of power lost in those devices.

### Hoist crane

The hoist crane should be installed in the irradiation hall with the slow rise of the hook (hand drive is possible), which allows one to serve a strip on each side from the axis lying above the center of the accelerator. The strip length should usually be no less than 4 m. Weight-carrying capacity depends on accelerator type.

### Instruction regarding anticorrosion protection

Selection of materials used in the construction installed in the accelerator chamber should be effected in such manner as to make proper provisions for the extremely high corrosive properties of the atmosphere in this room. This is caused by factors resulting from radiation with the beam of electrons, e.g. the presence of ozone and nitrogen oxides. It is recommended to use a paint resistant to peroxide acid.

Water cooling installations in the area of reaction chambers should be made from stainless steel. As far as the air supply and exhaust ventilation systems are concerned, it is recommended to make them from stainless steel, non-corrosive aluminium or alternatively regular steel covered with anticorrosive epoxy paint.

Cables, rubber hoses, parts made of rubber and teflon as well as units, instruments, plugs, panels located in irradiation zone and non-protected against the scattered electrons and active gases should be protected by shields of 1 mm thick made of lead or 2 mm thick made of steel.

Measures should be taken to avoid dust generation in the accelerator chamber. The walls, floor and ceiling must be covered by radiation proof materials.

## **3.3. Requirements for radiation protection**

Electron accelerators are high risk devices. Assembly and operation of such accelerators should take place in accordance with general operation, technical maintenance and safety

principles applicable to electric devices operating at industrial plants, as well as in accordance with principles for operating with ionizing radiation sources.

Scale of hazards is wide and complex. The safety system is an integral part of radiation facilities operation. Hazards evolve with facility age and mission. Regulatory environment of safety system includes:

- industrial safety (handling of potentially hazardous customer products; it can be referred to safety of machinery);
- radiation safety (integrate radiation requirements into industrial safety framework; it can be referred to radiation safety of electron irradiation facilities).

Safety control systems (SCS) should include:

- personnel safety systems:
  - access controls,
  - critical devices,
  - equipment interlocks,
  - audio and visual warnings;
- machine protection systems:
  - beam loss monitoring,
  - fast shutdown;
- safety envelope monitoring (access controls and interlocks);
- radiation monitoring.

The main objectives for radiation safety system are:

- keep people out of dangerous areas;
- warn people of hazards;
- define procedures, for example:
  - to secure radiation rooms,
  - to unsecure radiation rooms and allow access after a delay for ozone removal,
  - for emergency stop and access violations;
- provide safety even when a single fault is undetected.

Modern control systems are usually based on computer technology what directly leads to significant benefits related to irradiators operation in terms of process control and cost savings. However in that case the most important issue becomes safety system and its reliability and degree of safety. It is important for both new and upgraded irradiators. Presently offered control systems cover the entire irradiation process from loading of products to the final post-irradiation report. The facility monitoring system includes video surveillance as well as data transmission through internet and GSM network. Design features are the following:

- Diversity: Each safety interlock must function independently of any other safety interlocks. It is generally accepted that when using two identical devices in a redundant configuration the probability of both failing (to “danger”) is less than that of a single device.
- Reliability: It should provide the required protection, subject to all foreseeable aging and environmental conditions at the accelerator facility. These conditions may include weather extremes, high electromagnetic fields, high radiation fields, earthquakes, and the cumulative effects of aging on components, such as corrosion, dirt, and normal wear.
- Redundancy: The SCS is duplicated throughout (input devices, wiring, logic function, outputs), and is periodically tested to ensure that both “guard-lines” are operating correctly.
- Testable: Before commissioning, the system or subsystem shall be checked to meet the requirements. Pre-test and on-line tests are necessary.
- Fail safe: In case of failure, the SCS shall maintain a safe condition.

High power electron accelerator should be recognized as a powerful source of ionizing radiation causing hazard radiation effects when an accelerated electron beam is extracted into air. The radiation protection design should be done in accordance with the radiation safety rules accepted in certain country. During radiation protection calculation it is necessary to take into account the following radiation dangerous factors, which taking place during accelerator operating: electrons scattered by irradiated subjects in various directions, bremsstrahlung occurring



both while the beam deceleration in the irradiated subjects and due to its partial loss along the accelerating track and on the extraction device units.

Maximum bremsstrahlung energy for electron beam energy up to 5 MeV is lower than the threshold of photo-nuclear reactions for all elements except beryllium. Since there is no parts made of beryllium in typical accelerator facility, therefore it is radiation safe when electron beam is being switched off (with the absence of voltage on the resonator gap, or DC voltage in transformer accelerators).

With the beam absence but with high voltage presence at accelerating tube (in accelerating tube training mode, for example) it is possible the electrons auto-emission (so-called dark current) from accelerating tube upper electrodes and its electrons accelerating up to whole energy. In this case maximum air extracted electron beam can be 20-50  $\mu\text{A}$  range what creates real danger for personnel. When dark current is present the entry to accelerator chamber is strictly prohibited.

Safety control system should provide a personnel access system that will prevent unauthorized access to the treatment room. A mechanical and data interface should be defined to allow elements of the safety system to be installed at the entry to the treatment vault. It means that control system must recognize the cartons on conveyor and preventing any human intrusions.

Accelerator chamber (radiation-dangerous) should be equipped with protecting door (or labyrinths) for personnel passage and for accelerator devices transporting during accelerator assembling. Before the accelerator installation safety interlocks should be installed inside and at the entry to accelerator chamber:

- radiation dangerous illuminated indicator boards. These lamps are automatically switched on by accelerator control system during all time accelerator operation in radiation dangerous mode;
- sound signal system (high sound electric bell). These bells are automatically switched on by accelerator control cabinet during one minute every time before accelerator operation in radiation dangerous mode;
- hermetic buttons (toggle switchers) for fast accelerator break down in case of emergency;
- radiation protection door interlock.

During the operation of accelerators with accelerated beam of electrons, emergency situations (caused by radiation or fire) can take place in the following circumstances:

- damage of the door blockade at the radiation room,
- breakage of the biological shield,
- fire of switched on electrical devices.

In case of any emergency situation, all equipment should be switched off, work with accelerators stopped, while all people should be prevented from accessing the danger zone, local fire department, exposure measuring authorities and the company's administrative authorities should be notified. Accelerators can be switched on once reasons for the emergency are found, all damages are fixed and consent of the fire department and exposure measuring authorities are given.

### **3.4. Security system**

Overall security (physical security protection of radiation systems from outsiders) should be implemented. Certified redundant safety system using security elements should be designed to provide the full system to secure both the accelerator vault and the irradiation maze.

Security locks are to be engaged at different places. It shows the survey has been done inside the shielded cells and it gives the certainty there is nobody left inside the secured places. Beacons and flashing signals are associated to clearly show the status of the security system. The secured places are shown on a supervision screen and the secured status is one element of the "beam allowed general" signal.

### **3.5. Radiation monitoring**

Installation of meter with measurement range 0.01-1000  $\mu\text{Sv/h}$  connected with the adequate microprocessor, display and control unit is recommended. The probe should be set on the wall, inside the irradiation maze, at the vicinity of the exit. It will give an actual value close to the background very near the exit, any improbable significant variation will be an alarm. Sometime the second meter should be set in the accelerator vault as an unhooked with a cable long enough to reach selected components during the accelerator fine tuning. Portable measuring instrument is recommended as well.

### **3.6. Video control**

The high ionizing radiation background is present in the accelerator chamber. Installation video control system is mandatory. During the operation of the accelerator, the room will be inaccessible for maintenance services, but should be ensured by appropriately designed system of control and signalization. TV cameras installed in this room should be equipped with radiation protection shields, with the frontal parts of the cameras equipped with lead glass.

### **3.7. Ozone extraction**

An important problem of radiation installations is the level of ozone generated during the operation of the accelerator with the beam of electrons. Harmful effects of ozone are revealed at concentration above 1 ppm. It should also be mentioned that ozone can be felt at concentration as low as 0.01 ppm. For instance the American standard limits of daily exposure to ozone during an 8 h workday is set to 0.1 ppm. In some other countries this level is 0.06 ppm or even less.

The amount of ozone generated depends on the energy of electrons, electron beam current and the length of its travel through the air. The level of ozone generation is 0.11 kg/kWh where power corresponds to the electron beam energy losses per unit of time of travel through the air.

The value of calculated ozone concentration unambiguously determines the efficiency of the exhaust ventilation system. Neutralization of ozone is an additional problem. Ozone can be neutralized in the following ways:

- burning (thermal decomposition at temperature of 450°C),
- activated coal as a filter in the shape of granules with appropriate additives,
- application of magnesium dioxide filtration aid,
- dissipation through chimney.

The volume of air to be extracted is calculated in function of the maximum quantity of ozone which could be produced by the accelerator at full power. One can consider the maximum interaction between electrons and air (no obstacle). The height of the dissipation chimney can be calculated with the use of the formula with seated mandatory limit.

### **3.8. Water cooling system**

Several specific cooling water parameters may be taken into account: acidity value, carbonate hardness, specific resistance, input and output pressure, input water temperature. It depends on recommendation of accelerator manufacturer.

*Note.* Inlet water temperature should be not less than accelerator equipment dew-point.

Water consumption by the accelerator is specific for certain accelerator construction and it can vary between 50-200 l/min. Two close loops of water cooling system are applied the most frequently. First loop is connected to all accelerator components and heat exchanger. High quality or even distilled water is use in this particular loop. The other one usually contains ordinary

water. It is connected to cooling tower and heat exchanger. All components of the second loop are provided by investor. The water losses (consumption) in such system are very limited. The cooling system can be integrated in the whole building HVAC system.

#### 4. FACILITY DESIGN ASSUMPTIONS

##### 4.1. Plant production capacity

Calculation of mass productivity of radiation process is based on formula:

$$M = P \times F / D$$

where: M – mass productivity (kg/s), F – efficiency of beam energy transfer (0.2-0.7), D – absorbed dose (kGy), P – beam power (kW).

Coefficient of electron beam utilization depends on beam losses in exit window, losses in air, losses due to certain density distribution of irradiated material, losses due to geometry of scanned beam, losses due to packs density on conveyor and may be different for each type of product. The minimal F coefficient value was selected for productivity calculation and is equal to 0.3.

When four-sided irradiation is used the electron energy of accelerator can be selected within the range 2.5-10 MeV. The productivity according to the above formula for 1 kW beam power and 25 kGy dose rate can be:

$$M = 1 \text{ kW} \times 0.3 / 25 \text{ kGy} = 0.012 \text{ kg/s} = 43.2 \text{ kg/h}$$

Facility assumed to be operated 52 weeks/year. The national holidays can reduce this period to 50 weeks/year. It is recommended to perform general maintenance service during 5 working days after 6 months of facility operation. It reduces facility operating period to 48 weeks/year. Due to typical accelerator availability level 96%, facility operation period corresponds to 46 weeks/year, which means 1840 h/year (8 h for 5 days/week).

Table 5. Radiation facility productivity for different accelerators (average dose 25 kGy)

Accelerator type	Linac	Linac	Resonance	Resonance
Energy	10 MeV	10 MeV	5 MeV	10 MeV
Beam power	10 kW	15 kW	20 kW	40 kW
Productivity for one shift (1552 h)	670 t	1006 t	1341 t	2682 t
Productivity for two shifts (3392 h)	1465 t	2198 t	2931 t	5861 t

When one shift facility operation will be implemented the total operation time with electron beam will be limited to 1552 h/year for one shift because of 1 h/week should be devoted to current maintenance and 1 h/day (5 h/week) will be devoted to accelerator switching on and switching off procedures. Radiation facility productivity for different accelerators (average dose 25 kGy, beam utilization 0.3) is displayed in Table 5.

##### 4.2. Manpower and skills requirement

One shift operation requires two accelerator operators (technicians) and two workers for loading and unloading of the conveyor. There should be a facility manager who should be responsible for the overall operation of the facility as well as coordination other works related to outside service. It is recommended to engage one engineer responsible for maintenance and service work, who could replace operator due to vacation or other type of absence. One shift personnel should count six persons.

Additionally the facility should have a radiation safety officer and person responsible for technology dosimetry which should be performed in stated periods.

### 4.3. Location of the irradiation facility

Usually all the accelerator equipment is recommended to be located in three rooms. The other rooms (or storage surfaces) are related to radiation facility operation:

- control room (control console),
- power supply room (cabinets, high-vacuum pump power supply units),
- irradiation chamber (accelerator itself and auxiliary systems),
- storage before treatment (loading zone),
- storage after treatment (unloading zone),
- dosimetric laboratory (optionally).

The rooms before accelerator installation should meet requirements of vacuum hygiene. Before accelerator equipment installation all the sanitary-technical and decoration works should be completed, all the constructions and pipes should be cleaned and painted, the internal electrical power and grounding circuits and the light should correspond to the design.

The valves and pressure meters should be installed on the pressure and drain ends of water pipelines in the accelerator and power supply rooms. The pipelines should be tested. Operating consumption of cooling water should be provided.

The forced and exhaust ventilation should ensure the design proportion of the air exchange in the rooms according to the sanitary requirements for building design approved in Poland, it should be tested and accepted for operation.

The internal grounding circuits for the equipment frames should correspond to the design in all rooms.

The rooms and the doors as well as the roads should enable one to transport all the accelerator units with overall dimensions given in its documentation.

The control room should be protected against noise caused by the power supply system and the accelerated beam.

Measures should be taken within accelerator chamber (irradiation room) to avoid dust generation. The walls, floor and ceiling must be covered by radiation proof materials. Transportation of the accelerator parts into accelerator chamber thorough the shielding door (or labyrinths) should be foreseen in respect to certain accelerator part dimensions. If it is not possible it is recommended to make a hole at radiation protection walls with necessary dimensions. After the accelerator equipment installation that hole should be closed. The cable channels should be provided for accelerator equipment control and power supply. These holes location and dimensions as well as cable and water channels should be agreed upon the accelerator provider specialists before accelerator equipment installation.

Table 6. The approximate volume of shielding walls for different accelerators

Type of accelerator	Resonance	Linac	Resonance
Electron energy and beam power	5 MeV 20 kW	10 MeV 10-15 kW	10 MeV 40 kW
Approximate shielding wall volume (without floor layer on the ground level)	625 m <sup>3</sup>	900 m <sup>3</sup>	1500 m <sup>3</sup>
Approximate cost (approximate concrete price (with transport) ~100 €/m <sup>3</sup> )	0.3 M€	0.4 M€	0.6 M€
Surface needed for shield installation	90 m <sup>2</sup>	228 m <sup>2</sup>	372 m <sup>2</sup>

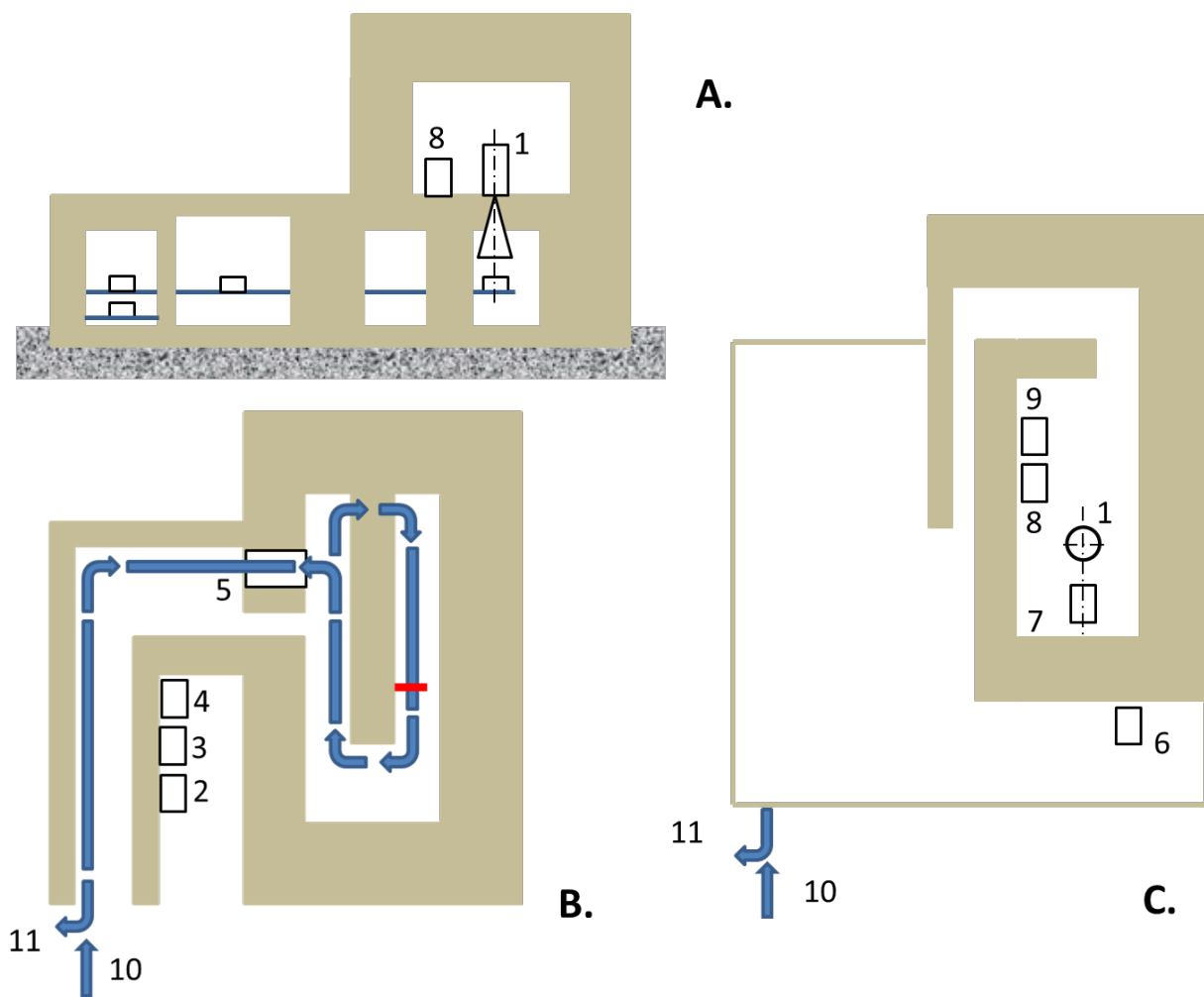


Fig. 19. Example of conveyor system lay out and shielding wall configuration in facility equipped with linear microwave accelerator: 1 – irradiator; 2 – control system of the conveyer; 3 – power supply rack; 4 – control system rack; 5 – overturn system; 6 – pulse modulator of the klystron; 7 – klystron; 8, 9 – two cooling system; 10 – loading zone; 11 – unloading in a zone. A – side view, B – ground floor top view, C – first floor top view

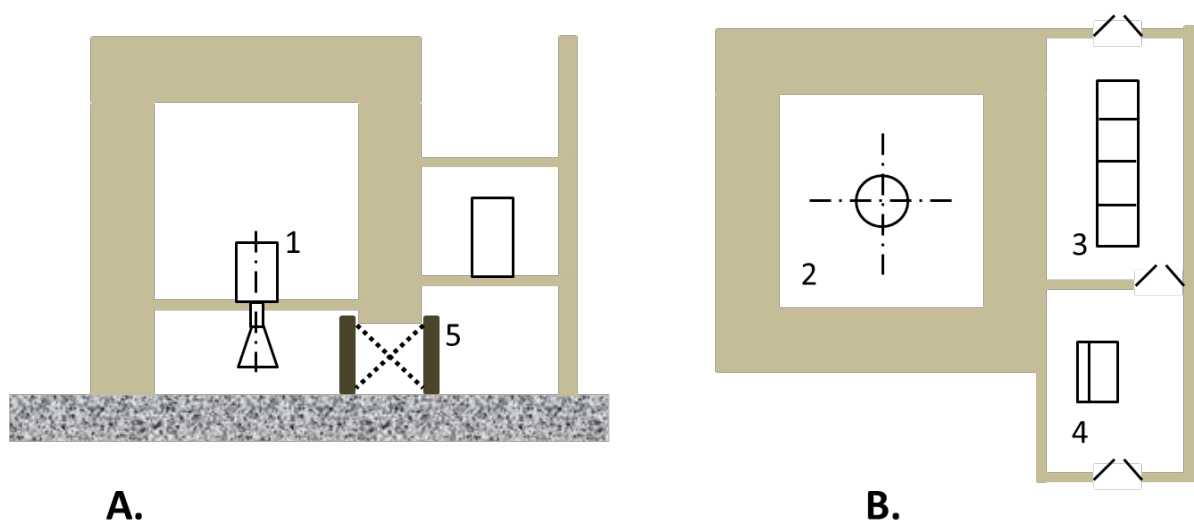


Fig. 20. Possible shielding wall configuration in facility equipped with RF single pass resonance accelerator: 1 – accelerator, accelerator chamber; 3 – modulator; 4 – control room; 5 – shielded door. A – side view, B – first floor top view

Arrangement of accelerator chamber depends on type of accelerator, its dimensions, conveyor system configuration and its shape of labyrinths through shielding walls. The shielding wall thickness depends mainly on electron energy, type of target material and shielding material density. The beam power level also has some influence on necessary wall thickness. The raw estimation of shielding walls shows that their thickness can vary from 2.5 m for electron energy 5 MeV to 3 m for electron energy 10 MeV. The precise calculations should be performed to evaluate exact shielding walls dimensions due to national regulation as well as due to shielding material density and shielding walls configuration including the presence of labyrinths for personnel and product entrance and channels for water pipes and electrical cables. Table 6 shows the approximate volume of shielding walls for accelerator chambers configuration presented in Figs. 19-21.

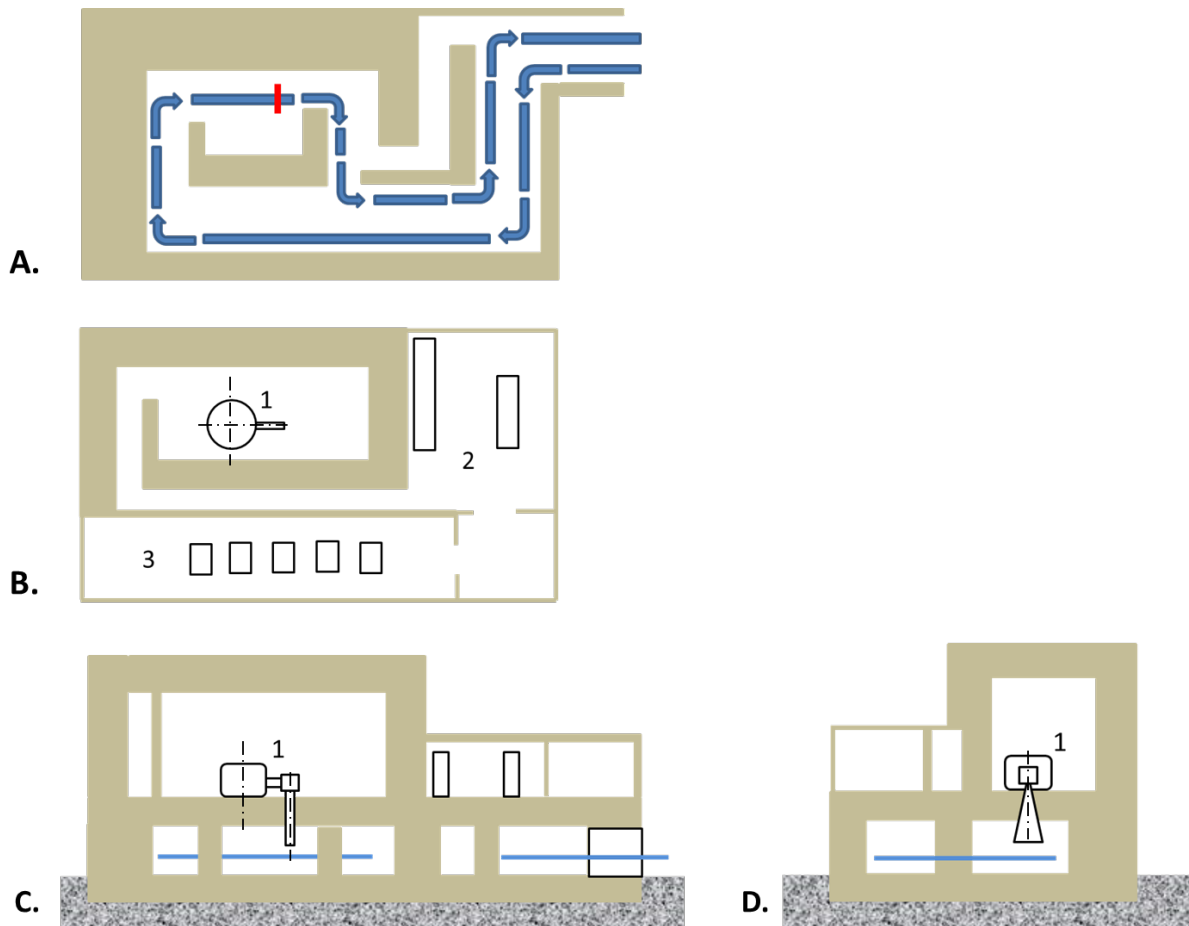


Fig. 21. Possible lay out of conveyor system and shielding wall configuration in facility equipped with RF multipass resonance accelerator: 1 – accelerator, 2 – control room, 3 – auxiliary equipment room. A – ground floor lay out; B – first floor lay out; C, D – side view

#### 4.4. Cost assessment

The investment and operating costs for electron beam accelerators vary widely because of different accelerator specification, type of accelerator and accelerator producers. High facility throughput which is directly related to the beam current level may significantly reduce total unit cost of the process. The accelerators with higher energy of electrons cost more than low energy devices with the same beam power level. Therefore, the lowest energy rating with suitable dose distribution in irradiated object will give better economical parameters of the radiation process. A reduction of the operating time would increase the unit cost significantly because fixed annual cost of investment will be allocated to fewer hours of accelerator exploitation. On

the other hand the lower dose will increase the process throughput and reduce the unit costs. Investment in general includes cost of accelerator and necessary building with shielding walls, safety interlock system, conveyor and auxiliary equipment, land, documentation and installation. Investment cost is frequently connected to the bank credit and became important part of operation costs which are also related to labor and administration spending, electrical energy consumption and spare parts.

Economical and financial evaluation should be performed to obtain information about commercial economical profitability of the project before its final approval and implementation. Economical evaluation should include structure of investment and operating cost of radiation facility. The economical effects of radiation installation may be influenced by many factors. The most important are the following:

- investment cost (direct and indirect costs);
- operating cost (variable and fixed costs);
- required dose level,
- utilization of electron beam and required dose homogeneity.

Cost reduction is one of the key factors of radiation technology successful implementation. Annual cash flow projections are common techniques used for analyses of economical options.

Economic analysis based on annual fixed and variable costs evaluation is very useful to prognosis and recognition of accelerator facility economical condition. Accelerator selection criteria are as follows:

- average beam power (productivity),
- electron energy (penetration),
- price (investment cost),
- electrical efficiency (cost of accelerator exploitation),
- size (building geometry and size),
- reliability (availability > 95%).

Estimated capital costs can be referred to electron accelerator price. One should take into account the expenses related to:

- shielding walls,
- ventilation,
- building with armature,
- technological equipment,
- process control system,
- design and permission,
- installation and validation.

Capital costs (investment),  $K_k$ , in relation to accelerator price,  $K_a$ , can vary in most cases according to simple formula given below:

$$K_k \sim 2.2 K_a$$

Capital costs (investment) includes direct and indirect cost components:

- direct costs:
  - the preparation of the stand,
  - construction of the building,
  - technological equipment;
- indirect costs:
  - project management,
  - facility design,
  - installation,
  - commissioning,
  - reserve.

Service (exploitation) cost can be divided on fixed and variable. Investment cost may have primary influence on fixed service cost, due to assumption related to amortization rate (5-10 years).

Exploitation fixed costs are as follows:

- administrative costs with overheads;
- security, amortization, credit;
- required license costs;
- service (planned);
- taxes, including land tax;
- insurance;
- annual regulatory permit fees;
- periodic verification or emission tests.

Exploitation cost includes variable cost components:

- labor (exploitation, supervision);
- electricity, water, pressured air, others;
- materials;
- spare parts.

In general, electron beam technology seems to have the low operating cost despite its moderate to high capital costs. The high capital cost of technology may be compensated by its relatively low annual operating costs. Full set of technical information should be collected to describe accelerator quality and evaluate the risk connected with certain accelerator design.

Table 7. Accelerator facility cost assessment

Accelerator type		Linac	Linac	Resonance	Resonance
Electron energy		10 MeV	10 MeV	5 MeV	10 MeV
Maximum electron beam power		10 kW	15 kW	20 kW	40 kW
Capital cost	accelerator	0.44 M€*	1.5 M€	1.0 M€	2.4 M€
	shielding	-	0.4 M€	0.3 M€	0.6 M€
	conveyor	-	0.25 M€	0.25 M€	0.6 M€
	others**	-	0.3 M€	0.3 M€	0.3 M€
	total	0.44 M€	~2.45 M€	~1.85 M€	~3.9 M€
Maintenance cost	E-gun	2.0 k€/y	2.0 k€/y	2.0 k€/y	3.0 k€/y
	ion pumps	2.5 k€/y	2.5 k€/y	2.5 k€/y	2.5 k€/y
	RF source	38.5 k€/y	38.5 k€/y	3.5 k€/y	7.5 k€/y
	others	2.0 k€/y	2.0 k€/y	2.0 k€/y	2.0 k€/y
	annually	~45 k€	~45 k€	~10 k€	~15 k€

\* Labor cost is not included.

\*\* Accelerator packaging and shipping, facility design and documentation, licensing, instrumentation, wiring and piping, security system, and ventilation.

The price of the accelerators and auxiliary equipment were evaluated on the literature data base in relation to electron energy and beam power level as well as differences in construction of particular devices. Such assumptions are necessary to calculate unit cost of operation.

Disadvantages and advantages should be discussed in details to optimize a final decision regarding accelerator selection. Table 7 presents the cost assessment of the radiation facility with medium or high energy high power electron accelerator. The capital cost which included the accelerator, shield vault, handling system totally amounts of 1.85 to 3.9 M€ Annually, the maintenance cost depends on accelerator type and vary from 10 to 45 k€(1 to 5% of accelerator cost).



Table 8. Accelerator facility operating cost assessment

Accelerator type	Linac	Linac	Resonance	Resonance
Energy activity	10 MeV	10 MeV	5 MeV	10 MeV
Initial investment	0.44 M€	2.45 M€	1.85 M€	3.9 M€
Power consumption	150 kW	225 kW	155 kW	235 kW
Fixed cost	administration and others*	43.2 k€	43.2 k€	43.2 k€
	depreciation **	88 k€	490 k€	370 k€
	subtotal	131.2 k€	533.2 k€	413.2 k€
Variable cost for one shift	labor	86.4 k€	86.4 k€	86.4 k€
	electricity	27.6 k€	41.4 k€	28.5 k€
	spare parts	45 k€	45 k€	10 k€
	service	30 k€	30 k€	15 k€
	subtotal	189 k€	285.1 k€	128.9 k€
Total annual cost	320.2 k€	818.3 k€	542.1 k€	977.9 k€
Maximum one-hour productivity***	432 kg	648 kg	864 kg	1728 kg
Cost of 1 h electron beam operation	206 €/h	444 €/h	295 €/h	630 €/h
Unit cost	0.48 €/kg	1.26 €/kg	0.63 €/kg	0.36 €/kg

\* Administration, outside service for planned maintenance, dosimetry service, radiation safety officer.

\*\* 5-year period.

\*\*\* Dose rate 25 kGy, electron beam utilization coefficient 0.3.

The data related to accelerator facility operating cost assessment are presented in Table 8. In conclusion, one can find the unit cost of product irradiated by different accelerators in relation to 1 kg of the product and the one-hour productivity. The calculations were performed for one shift operation.

#### 4.5. Permissions

The procedure of the realization of the investment should include certain steps:

- pre-feasibility study (multivariants conception),
- the choice of the variant,
- the study of feasibility – the chosen variant.
- project related to the conditions of the building and land development,
- obtainment of the conditions of the buildings and land development,
- technical project of the building and project of permission on the building,
- obtainment of permission on the building,
- the realization.

Initiation of investment process requires standard procedures related to acceptance (permission) of local authorities supported by report related to potential influence on environment.

The specific procedures are related to separate permissions which allow to initiate construction, starting up and exploitation facilities equipped with sources of ionizing radiation. Such permission is provided by the Nuclear Safety Department of the National Atomic Energy Agency, Poland (PAA).

Accelerator operators should obtain official license to operate accelerator facility. Formal proposal (document available on web page of the PAA) should be supply to the Nuclear Safety Department of the PAA. After positive results of national exam the license will be provided. The training course on radiation safety matters for accelerator operators is strongly recommended in advance to national exam. The list of organization providing necessary training courses is available on web page of the PAA.

#### **4.6. Cooperation**

The Centre of Radiation Research and Technology of the Institute of Nuclear Chemistry and Technology activities include basic research, development and applications, various services related to the profile of its activities. The Centre is the best developed in Poland in the fields of implementation of electron beam technology and radiation chemistry. The results of works have been implemented in various branches of national economy, particularly in industry, medicine, environmental protection and agriculture. Nowadays with its six electron accelerators and three laboratory gamma sources in operation and with the staff experienced in the field of electron beam application, is one of the most advanced centers of science and technology in this domain. The Centre has four pilot plants: for radiation sterilization of medical devices and transplantation grafts, for radiation modification of polymers, for removal of SO<sub>2</sub> and NO<sub>x</sub> from flue gases, for food hygienization and has long time experience in practical implementation radiation processing technologies including number technologies related to polymer modifications (thermo-shrinkable tubes and tapes, wires and cables, foams).

Gained experience would be the excellent base for future cooperation in number fields of activities:

- participation in preparation of proposals to support implementation of new energy efficient technology from national sources,
- polymer material characterization towards certain properties development,
- optimization of the irradiation process of products of different geometry and composition based on experimental and computational methods,
- training capability in operation and exploitation accelerator facility,
- participation in supervision of electron accelerator installation,
- participation in facility commission procedures,
- routine technological dosimetry with certified method,
- radiation safety and personal dosimetry.

### **5. CONCLUSIONS AND RECOMMENDATIONS**

The data presented in Tables 7 and 8 show that electron beam facility equipped with presented accelerators are capable to irradiate required amount of required product. The electron energy levels 5 and 10 MeV were considered. A more detail technical analysis should be performed to recognize optimal conditions of irradiation process. Final result depends on geometry irradiated product, nominal energy of the accelerator and configuration of irradiation process. Due to specific product dimension two-sided irradiation could be solution to improve the process efficiency, and irradiation homogeneity. Such process can be performed by electron beam with energy 5 or 10 MeV.

A more detailed financial analysis on the profitability of the process should be undertaken after selection certain accelerator to implement radiation processing. Table 8 shows main advantages and disadvantages of certain accelerator constructions. The possible reason of difference would be the specific beam utilization coefficient or significantly lower beam power provided by the facility. Other limit can be present due to ability to perform the irradiation process fast enough (conveyor speed) to use the full beam power.

Table 9. The main advantages and disadvantages of certain accelerator construction

Accelerator type		Linac	Linac	Resonance	Resonance
Energy activity		10 MeV	10 MeV	5 MeV	10 MeV
Initial investment		0.44 M€	2.45 M€	1.85 M€	3.9 M€
Beam power		10 kW	15 kW	20 kW	40 kW
Advantage	high beam power				X
	compact size	X	X	X	
	low investment cost	X	X	X	
	lowest spare parts cost			X	
	lowest unit cost				X
Disadvantages	low beam power	X	X		
	high investment cost				X
	highest unit cost		X		
	highest spare parts cost	X	X		
	low energy level			X	

Table 9 shows main advantages and disadvantages of facilities based on different accelerators. Facility based on resonance multipass accelerator is fully acceptable from technical point of view, but it is characterized by relatively high investment cost. Microwave linacs are characterized by relatively low beam power, as well as relatively high spare parts cost. More universal production profile would be obtained with resonance single pass accelerator due to high enough electron energy level (up to 5 MeV) and moderate beam power.

The detailed analysis should be performed regarding product profile and selection of irradiation configuration and conveyor technical capabilities and properties. Traditional conveyor system seems to be more universal for different types of irradiated product.

#### *Acknowledgements*

*This work is financed by international collaboration project H2020 ARIES (EU) “Accelerator Research and Innovation for European Science and Society” and the Ministry of Science and Higher Education (Poland) co-financing project.*